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EXPERIMENTAL CONSTRAINTS ON THE SCALE OF NEW PHYSICS IN TOP CONDENSATE MODELS

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Abstract

We obtain mass limits on the extra neutral gauge boson which is predicted in a model with hidden gauge symmetry and dynamical breaking of the electroweak symmetry by a top quark condensate. For typical model assumptions, present LEP data exclude masses below 3 TeV. With LEP200 or an electron-positron collider of a c.m. energy of 500 GeV masses below 15 TeV or 50 TeV could be excluded, respectively. Such high mass limits allow the calculation of the observables used in the analysis in the context of the Nambu-Jona-Lasinio model.

1. Introduction

It is well known that precision experiments at e^+e^- colliders can give indirect limits on masses of extra neutral gauge bosons. However, the best mass limits on weakly coupled gauge bosons are usually set by direct production at hadron colliders. In this letter, we consider a model which contains an extra, strongly coupled neutral gauge boson originating in top condensate models. We derive mass limits from present and future e^+e^- colliders and find that here they are superior in comparison with hadron colliders.

The large mass of the top quark motivates a specific dynamical breakdown of the electroweak symmetry by the formation of a top quark condensate [1]. The Top Mode Standard Model (TMSM) possesses scalar four fermion interactions of Nambu-Jona-Lasinio type instead of elementary scalar Higgs-fields, [2] - [5]. In its minimal form [5] it hardly matches the experimentally allowed top mass window [6]. Moreover, the TMSM has been found unsatisfactory for theoretical reasons concerning predictability beyond the Standard Model (SM) [7, 8]. The naturalness requirement demands the scale of next physics beyond the SM to be in the TeV range. Here, far below a GUT scale, one does not expect to already leave the framework of quantum gauge field theories and the TMSM has never been meant to solve the fundamental mass problem. The simple possibility to assume a well-defined gauge theory as the origin of the NJL-type model [8] attempts to find the structure beyond the SM in using the fact of the large top mass. A variety of gauge extensions to $SU(2)_L \times U(1)_Y \times G$ was proposed on these grounds [9, 10, 11]. The breaking of non-standard symmetries is thereby often described by scalar fields and this does not disturb the concept of looking for structures at the TeV scale. The value of the new scale, related to the mass of new bosons, is essential for theoretical predictions of the models.

In this letter, we derive lower bounds for the mass of non-standard gauge bosons within the Hidden Symmetry Model [11] from e^+e^- data.

In section 2 we briefly introduce the features of the Hidden Symmetry Model needed for the analysis of experimental data. In section 3 we describe the analysis and discuss the results. We conclude in section 4.

2. The Hidden Symmetry Model

The extension to the hidden gauge group $SU(2)_V$ has been discussed in [13] and recently in [14]. It was applied to the top condensate mechanism in [8, 11].

Starting point is the symmetry $SU(2)_L \times U(1)_{Y'} \times SU(2)_V$. [As none of the features of the model, which make it special for top quark condensation, depends on the dimension of the hidden group, it could as well be any hidden $SU(N)$ including $U(1)$.] $U(1)_{Y'}$ differs from the standard $U(1)_Y$ only by the definition of the gauge coupling constant. $SU(2)_V$ is a hidden symmetry, i.e. fermions are standard: they do not possess new degrees of freedom and transform as singlets. These local symmetries are broken down to electromagnetism in two steps:

$$\begin{array}{lll} SU(2)_L \times U(1)_{Y'} \times SU(2)_V & \overset{spontaneously\ by\ scalars}{\longrightarrow} & \\ SU(2)_L \times U(1)_Y & \overset{dynamically\ by\ \langle\bar{t}t\rangle}{\longrightarrow} & U(1)_{em} \end{array} \tag{1}$$

The first step looks very much like the spontaneous symmetry breaking in the SM, but here $\mathrm{SU(2)}_V \times \mathrm{U(1)}_{Y'}$ is broken down to $\mathrm{U(1)}_Y$. Diagonalization causes a mixing of primordial

$\mathrm{U}(1)'_Y$ and $\mathrm{SU}(2)_V$ fields $\bar{B}$ and $\bar{V}$ to a massless B and a massive v^0 in the neutral sector. The mixing angle ξ is given by

$$\sin\xi = \frac{g'}{\sqrt{g''^2 + g'^2}}. \tag{2}$$

Between the new scale and the Fermi scale, i.e. in the $SU(2)_L \times U(1)_Y$ symmetric phase, the interaction of neutral gauge bosons with fermions is given as [11]

$$\mathcal{L}_0 = g J_i^\mu W_{\mu i} + g' \cos\xi J_Y^\mu B_\mu - g' \sin\xi J_Y^\mu v_\mu^0. \tag{3}$$

J_i^μ and J_Y^μ are exactly the SM-isospin and hypercharge currents. $g' \cos\xi$ is restricted to have the value of the standard hypercharge gauge coupling constant. Charged heavy bosons $v^\pm$ do not couple to standard fermions.

A strong coupling

$$(g' \sin\xi)^2 \frac{2}{18} > \frac{8\pi^2}{N} = G_c \tag{4}$$

causes the condensation of $\bar{t}t$. Down type quarks do not form condensates because of a repulsive interaction by means of the hypercharge quantum numbers. In flavor space, the mass matrix has rank one, so that finally only the top achieves a mass as wanted [9]. The present model is special in not assuming a heavy top quark. Instead, the only source of explicit $SU(2)_R$ violation in the SM, the hypercharge, is used to produce a heavy top and a light bottom quark.

The strongly interacting new sector, eq. (4), cannot be treated with perturbation theory. It is handled by ladder approximation and an expansion in p^2/M_v^2, where M_v is the mass of the new neutral gauge boson and p is the typical energy scale, i.e. $p^2 = M_Z^2$ for LEP I. Both expansions must be motivated. The ladder diagrams are dominant in summing over an appropriate large number N of fermionic degrees of freedom. There is a very close connection of the large N expansion to the resulting mass matrix [12]. In the Hidden Symmetry Model, N is hidden and understood to carry information of the inner structure of fermions. (It is not related to the size of the hidden gauge group.) The restriction to first order in p^2/M_v^2 allows the analytical calculation of bound states, because ladder diagrams sum as geometric series in this limit. This approximation can always be used as will be shown by experimental limits on M_v. Deviations from these approximations would modify the relation of m_{top} to the ρ-parameter, as discussed in the minimal TMSM [5, 15]. Other sources of deviations from those predictions are vector resonances, which should additionally appear in the gauge models.

A typical model assumption is $N = 3$. The corresponding critical coupling is

$$g' \sin\xi > \nu 2\pi\sqrt{6} = 2\pi\sqrt{6}, \quad \nu = \sqrt{3/N}. \tag{5}$$

3. Analysis of e^+e^- Data

We now search for mass limits to the extra neutral gauge boson V from present and future electron-positron colliders. The remarkable agreement of present experiments with the SM fix its parameters with high precision and leads to definite predictions at higher energies. A direct production of extra neutral gauge bosons in e^+e^- collisions is very unlikely because of present mass limits from hadron colliders. Although, it can be observed indirectly, if one observable deviates from the SM prediction more than the expected experimental uncertainty.

In our analysis, we take into account statistical and systematic errors as well as radiative corrections. We assume an integrated luminosity of $L_{int} = 20 fb^{-1}$ at $\sqrt{s} = 500 GeV$ for a linear electron positron collider (Linac) and $L_{int} = 0.5 fb^{-1}$ at $\sqrt{s} = 190 GeV$ for LEP200, which corresponds roughly to one year of running time. Dominant systematic errors at the Linac (LEP200) are due to luminosity uncertainty and the errors of lepton and hadron energy measurements of 1% (0.5%), 0.5% (0.5%) and 1% (1%), respectively [16].

The necessary QED corrections are taken into account including a cut Δ on the photon energy $E_\gamma / E_{beam} < \Delta = 0.7$. Δ is needed to remove the radiative tail and to suppress the background [16].

We use an extended version of the program `ZCAMEL` [16] for the calculation of observables (cross sections and asymmetries). It includes the full $O(\alpha)$ QED corrections in theories with extra neutral gauge bosons and soft photon exponentiation [17]. We include the following observables in our analysis

$$\begin{aligned} &\sigma_t(\bar{l}l),\ A_{FB}(\bar{l}l),\ R = \sigma_t(\bar{l}l)/\sigma_t(\bar{q}q),\ A_{LR}(\bar{l}l), \\ &A_{LR}(\bar{q}q),\ \sigma_t(\bar{b}b),\ A_{FB}(\bar{b}b),\ A_{LR}(\bar{b}b),\ P_\tau,\ P_\tau^{FB}, \end{aligned} \tag{6}$$

where $\bar{l}l$ ($\bar{q}q$) refer to the production of leptons (5 quarks), respectively, and P_τ and P_τ^{FB} are τ polarization asymmetries.

We found that for LEP200 and for the Linac the total cross section of lepton production gives the best mass limits to the V-boson mass. For the special case $N = 3$, we obtain

$$\begin{aligned} M_V &> 15\,TeV, \quad 95\% \text{ c.l. for LEP200}, \\ M_V &> 50\,TeV, \quad 95\% \text{ c.l. for the Linac}. \end{aligned} \tag{7}$$

Beam polarization can improve these bounds due to the left-right asymmetry of hadron production $A_{LR}(\bar{q}q)$. For $N \neq 3$, the limits are shown in Fig. 1 and Fig. 2.

The mass limits from LEP I data are different. In a full analysis one has to constrain the Standard Model parameters, the mass of the extra neutral gauge boson and its mixing with the Z-boson simultaneously [18]. LEP data constrain mainly the mixing. In the Hidden Symmetry Model there is no mixing between the Z and V by definition because they are mass eigenstates.

A full analysis of LEP data in the Hidden Symmetry Model has not yet been done. However, we observed that the leptonic forward-backward asymmetry at the Z-peak $A_{FB}(\bar{l}l)$ is much more sensitive to M_V than the other observables at LEP. We obtained an approximate mass limit to the V by the following procedure: We took the observables

$$P_\tau,\ P_\tau^{FB},\ A_{FB}(\bar{b}b),\ A_{FB}(\bar{c}c),\ A_{FB}(\bar{q}q), \tag{8}$$

measured at the Z-peak [19] and their errors and calculated a prediction for $A_{FB}(\bar{l}l)$. It is, of course, consistent with the measured value of $A_{FB}(\bar{l}l)$. Demanding that an additional neutral gauge boson V should not spoil this consistency leads to the mass limits shown in Fig. 2. For $N = 3$, we get

$$M_V > 3\,TeV, \quad 95\% \text{ c.l. for LEP I}. \tag{9}$$

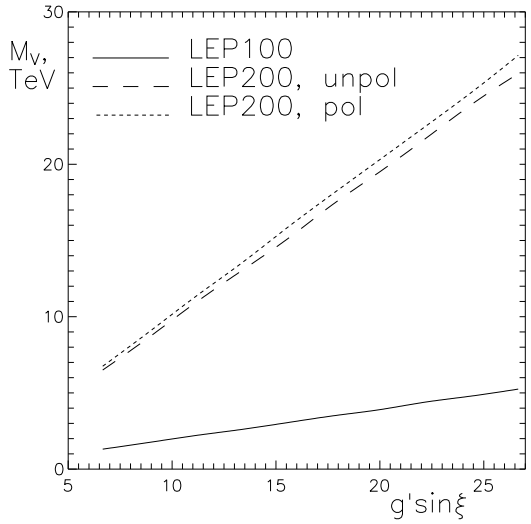

Fig. 1: *The LEP mass limits for the additional neutral V-boson as function of the coupling strength.*

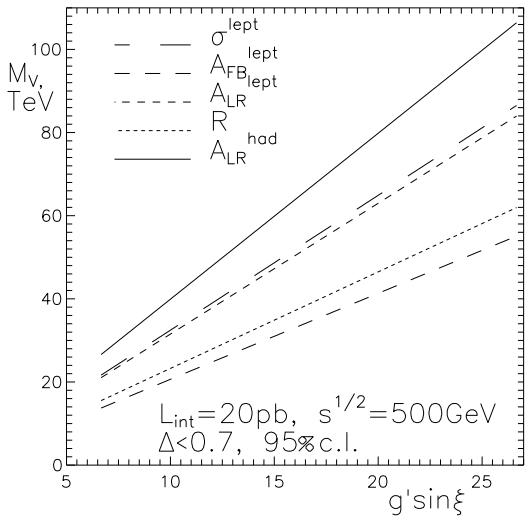

Fig. 2: *The 500 GeV collider mass limits for the additional neutral V-boson as function of the coupling strength.*

The mass limits (7), (9) have a linear dependence on the coupling constant $g' \sin\xi$, see Fig. 1, Fig. 2. This is due to the large $V-$fermion coupling enabling us to be sensitive to V-bosons, which are much heavier than the c.m. energy. Thus, a deviation of any observable from the SM prediction depends only on the ratio $g' \sin\xi / M_V$ and not on $g' \sin\xi$ and M_V separately:

$$\text{SM} \; - \; \text{Hidd. Symm.} = -\text{const.} \frac{(g' \sin\xi)^2}{s - M_V^2 + i\Gamma_V M_V} \approx \text{const.} \left(\frac{g' \sin\xi}{M_V} \right)^2 . \qquad (10)$$

The obtained limits on the V-mass constrain the mass scale of the hidden symmetry breaking to be much larger than the mass scale of the electroweak symmetry breaking, i.e. for all considered electron-positron colliders $s/M_V^2 \ll 1$. Hence, higher orders of the parameter s/M_V^2 can be neglected and observables can be calculated in the Hidden Symmetry Model. Here we obtain consistency with our preliminary assumption needed for the experimental analysis. The case of a light V-boson can be also excluded because it would have shown up in hadron colliders or by an inconsistency of the observables at LEP with the SM due to its large couplings to all fermions.

Finally, we mention that we assumed the absence of unknown non-decoupling resonance effects of the hidden strong interaction in the observables (6).

4. Conclusion

Compared to hadron colliders, electron-positron colliders are superior in setting mass limits to strongly coupled extra neutral gauge bosons V. For the Hidden Symmetry Model considered here, these bosons must be heavier than 3 TeV to be consistent with present LEP data. LEP200 or an e^+e^- collider with a c.m. energy of 500 GeV would improve these limits to 15 TeV or 50 TeV.

As a consequence, higher orders in p^2/M_V^2 can be neglected, so that ladder diagrams can be summed as usually done in the NJL model and reliable predictions can be derived.

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